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LOADING, ELECTROMYOGRAPH, AND MOTION DURING EXERCISE

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ABSTRACT

A bicycle ergometer system has been developed to determine forces acting in specific muscles and muscle groups for both cycling and isometric exercise. The bicycle has been instrumented with encoders, accelerometers, and load cells. A harnessing system has been developed to keep subjects in place during isometric exercise. EMG data will also be collected with electrodes attached to various muscles on the subject's leg. Data has been collected for static loading and will be collected for cycling in both an earth-based laboratory and on the KC-135. Once the data is analyzed, the forces will be entered into finite element models of bones of the lower extremities.

A finite element model of the tibia-fibula has been generated from the experimental subject's MRI data. The linear elastic isoparametric brick elements representing the bones are connected by linear elastic isoparametric shell elements placed at the locations of ligaments. Models will be generated for the calcaneus and the femur. Material properties for the various tissues will be taken from the literature. The experimentally determined muscle forces will be applied to the models to determine the stress distribution which is created in the bones.

INTRODUCTION

Under weightless conditions, astronauts have exhibited a tendency to develop osteoporosis in their lower extremities. For locomotion, they push off the walls of the orbiter with their arms, but the usual forces of a gravitational environment are no longer applied to their legs. With the projected loss of bone in the femoral neck, missions over 11 months in duration will put 40-year-old astronauts in a moderate fracture risk category equivalent to a 70-year-old. According to Wolf's Law, bone adapts to functional demands by remodeling to reflect the distribution of effective stresses. [1] Exercise countermeasures which impose an earth-like stress distribution on the bones of the lower extremities will have a positive affect on bone density loss.

This report describes the initial phase of a long-term project in which various exercise devices will be studied to determine their effectiveness in the prevention of bone density loss. A bicycle ergometer has been instrumented with accelerometers, position encoders, and load cells. From this instrumentation and electrodes attached to a subject's leg, force data will be taken both on earth and in the weightless environment of the KC-135. This data will be analyzed to determine the forces acting in each of the major muscle groups of the lower extremities. This dynamic force data will then be entered into finite element models of the tibia-fibula, femur, and calcaneus to calculate the stress distribution throughout these bones in both the one-g and zero-g environments.

EXPERIMENTAL EQUIPMENT

The data acquisition system and the equations for analyzing the accelerations and forces on the bicycle are described in report #11 by Dr. Figueroa. Traditionally, this type of data is collected by photographing an activity using two cameras mounted at a sufficient distance to view the entire scene. The data acquisition system was developed for the bicycle ergometer with the confined quarters of space vehicles in mind.

ELECTROMYOGRAPHY

To determine forces acting on individual muscles, electromyographic data is used. During the motion of bicycling, the primary movements are ankle extension and flexion. However, numerous other muscles in the leg are also activated. These secondary muscles, such as the peroneus longus, contribute to such things as stabilization of the ankle joint. Countering forces are applied to the bones which are not easily measured as external work. The primary hypothesis of this project is that secondary muscles apply loads to the bone which can be

beneficial in preventing bone loss.

Data for determining the EMG/force relation for a variety of calf muscles was collected. With the assistance of Gary Dudley, Ph.D. and William Norfleet, M.D., measurements were made on individual muscles with corresponding torques measured on the LIDO.

EMG electrodes were placed on a female subject's left leg at the following locations: peroneus longus, lateral gastrocnemius, medial gastrocnemius, soleus, flexor hallucis, peroneus brevis, extensor digitorum longus, and tibialis anterior. Measurements were made on the left calf with the knee moving from extension to flexion at rates of 30 and 90 degrees per second while the subject was in a seated position. Measurements were repeated for the left ankle with the subject in a kneeling position, and they were also made for unilateral and bilateral stances and toe raises with eyes open and closed. These measurements were repeated after local lidocaine injection about the motor point of each muscle group. After the first injection, all toe extensors and a majority of the tibialis anterior were eliminated. The second injection eliminated the peroneus longus; after this injection, the subject had no dorsiflexion. The third injection eliminated the soleus and left minimal function remaining in the calf. The toe flexors remained intact. Injection four may have eliminated the tibialis posterior. More will be known about the effect of that injection when the data is analyzed. The fifth and final injection was in the adductor canal proximal to the peroneal nerve branch. All motor functions below the knee except the supination-plantar flexion (tibialis posterior, flexor digitorum longus, and flexor hallucis longus) were eliminated. Complete use of the calf muscles returned to the subject a few hours after the last injection.

A sample plot of the raw EMG data is shown in Figure 1. The square curve is the signal associated with the recorder being activated. The signal following that is the EMG.

EMG and force data were also collected off of the left leg of the same subject under static conditions. A harnessing system was developed to keep the subject connected to the bicycle ergometer while the subject exerted maximal effort with the instrumented leg.

Additional data will be collected from this subject while cycling. This data will be collected both in an earth-based laboratory and on the KC-135.

DATA ANALYSIS

The experimental data will be analyzed with the computer package MATLAB. The EMG data will be analyzed using traditional procedures. [2] The

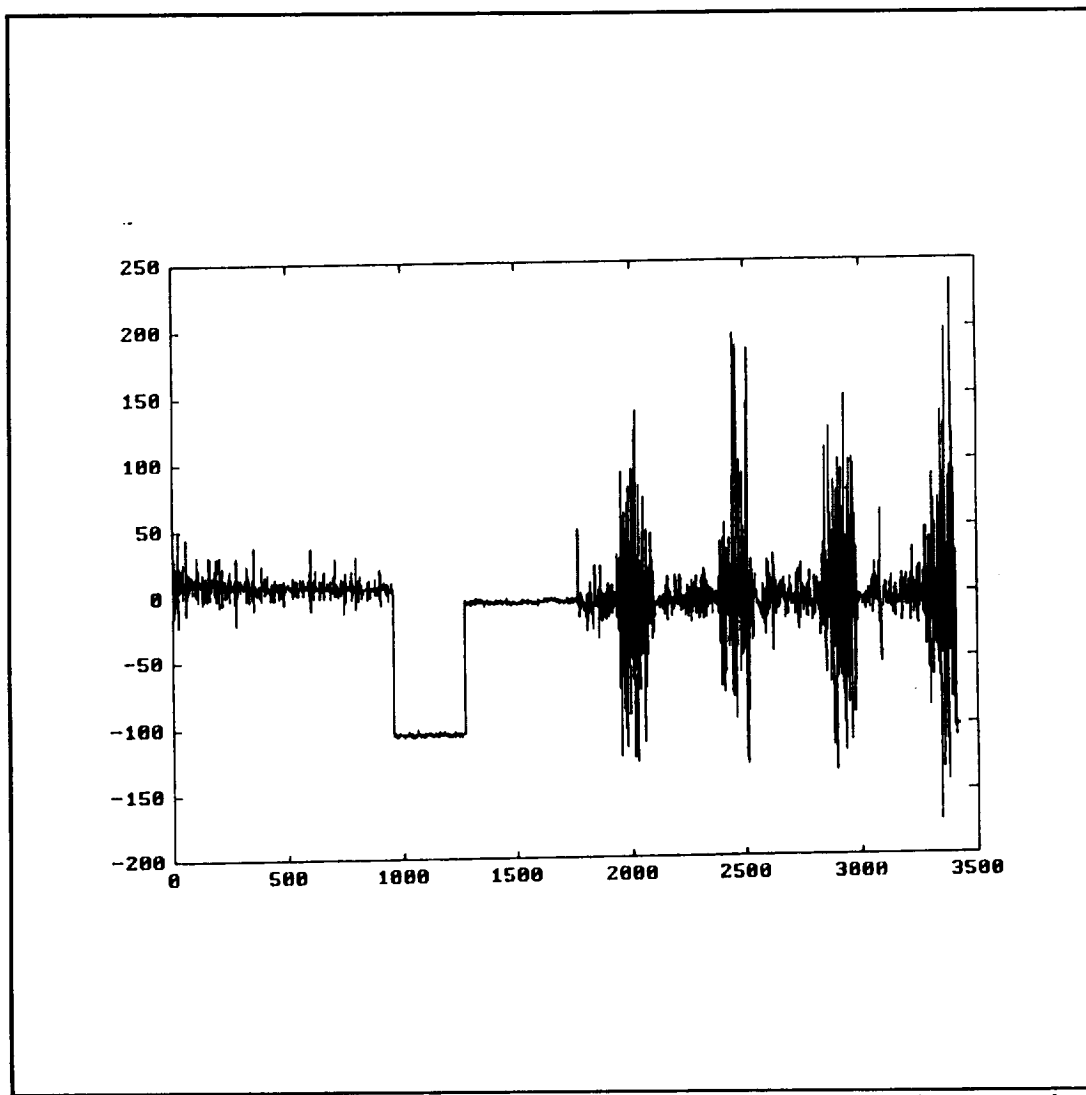


Figure 1 EMG signal for lateral gastrocnemius while subject is free-wheeling on ergometer.

accelerometer, load cell, and encoder data will be analyzed with the equations developed in report #11. [3] Forces acting at specific locations of the bones of the lower extremities in different situations will be calculated from this analysis. These resulting forces will be used in the finite element model to calculate the stress distributions in the calcaneus, femur, and tibia-fibula.

FINITE ELEMENT MODELING

The bones of greatest interest are the tibia-fibula, femur, and calcaneus. To determine the stress distribution in each of these anatomical structures, finite element models are needed for each of them.

Geometry

The geometry for the finite element models is based on data taken with Magnetic Resonance Imaging (MRI). Additional details around the joints of the bones were determined from x-rays. The use of these imaging techniques will allow the generation of models which will correspond to individual experimental subjects as opposed to a general-purpose generic model.

Eighty-two images of the subject's right leg were made. Slices 9 to 38 were 256x256 bit transverse images of the calf spaced 12 mm apart. Slices 7, 8, and 51 to 82 were 256x256 bit transverse images of the thigh spaced 12 mm apart. The other images were sagittal and coronal views of the body. Data from the images were transferred into *.bitmap (*.bmp) files.

PAINTBRUSH was found to be the most useful IBM-compatible software for determining nodal coordinates for the final element model. The *.bmp files were read into PAINTBRUSH, and the bone was identified. Twelve nodal points were identified around both the inner and outer edges of the bone for each slice. Using the Zoom feature with Cursor Position turned on, pixel coordinates for these points were recorded. One of the MRI slices for the calf is shown in Figure 2.

The pixel coordinates for each of the nodes were converted into mm with MATLAB. (Conversion factors are 0.488 for the calf and 0.781 for the thigh.) Then an input file was constructed for the PC-based finite element program PRIME. [4] The geometry for six 36-mm long regions was generated with PRIME. The geometry had to be generated in these regions due to the large amount of memory required by the whole model as compared to the 4 Mb of RAM which were available on the IBM-compatible 386 used for this project. The complete model will be generated on a DECStation 5000/240 with 40 Mb of RAM running at approximately 50 mips and solved on that computer as well as an IBM RS6000.

The model of the tibia-fibula is nearing completion. Currently the model contains 1242 nodes and 696 elements. The bones are constructed from 8-node linear orthotropic isoparametric brick elements. They are connected with 4-node and 3-node linear isotropic isoparametric shell elements which are placed at the locations of the ligaments. [5] Shell thicknesses vary from 5 to 8 mm depending on their location. [6,7]

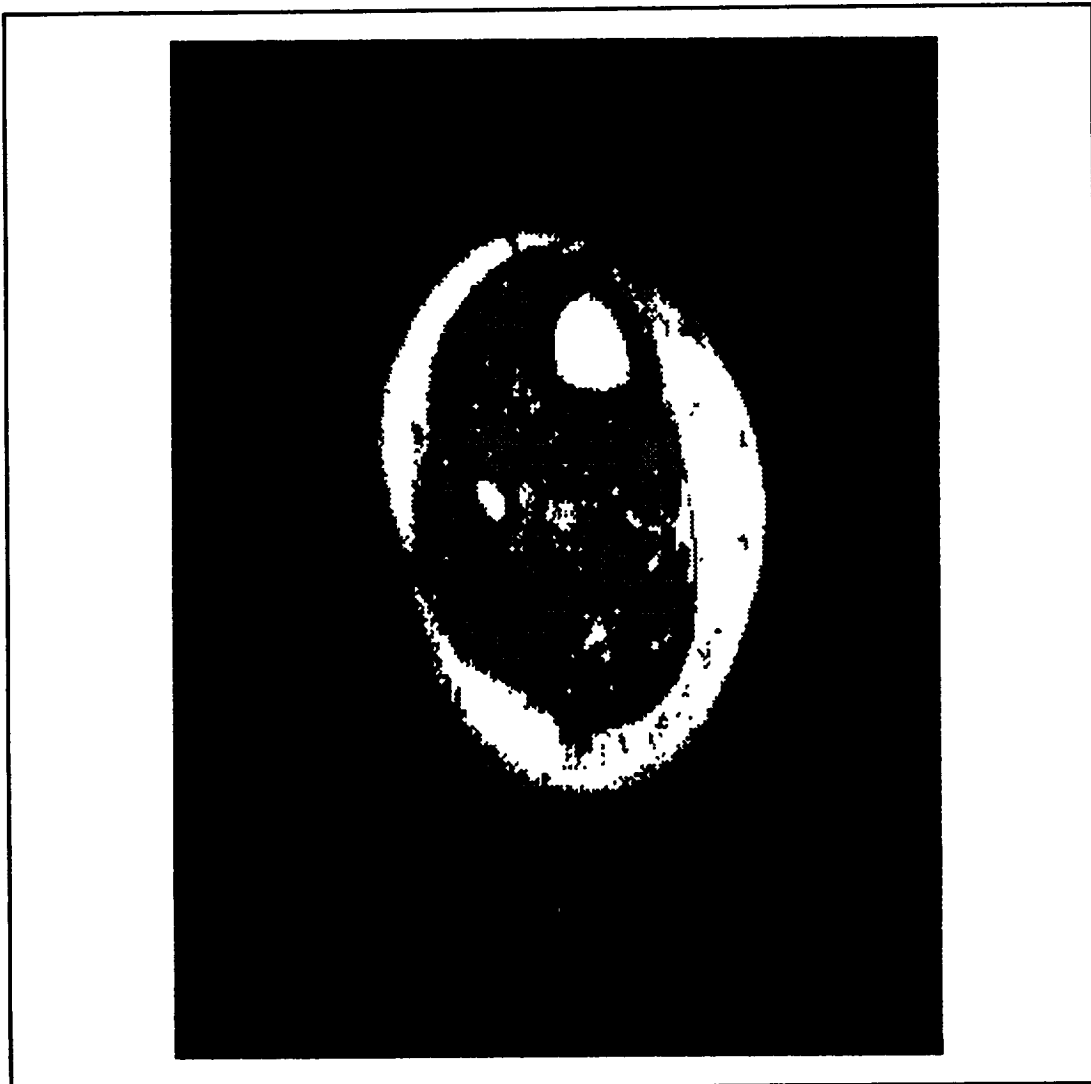


Figure 2 MRI slice 30 of the right calf.

Material Properties

Material properties for the models will be taken from the literature. For the elements representing ligaments, Young's Modulus, E , was set to 8.33 MPa with Poisson's Ratio, ν , as 0.49 based on published data. [8]

For bone, there are numerous articles available which discuss their material properties. [9-29] Values vary as a function of storage method, testing conditions, specimen configuration, specimen orientation, anatomical origin, porosity, density, and ash content. [20] Some values appear to be influenced by the aims of the research. [30] Some published values appear to conflict with other published values. [30] Some values [12,13] fall outside of theoretical limits, such as

Poisson's Ratio calculated to be greater than 0.5. [31,32] Clearly, the literature must be understood thoroughly so that accurate material properties can be chosen. Currently, $E = 15500 \text{ MPa}$ and $\nu = 0.28$. [33] It is expected that a more thorough examination of the literature will result in modifications to these values.

In particular, the orthotropic properties of bone will be considered. Reilly and Burstein have determined five elastic constants which describe the orthotropic properties of bone: E_1 , E_3 , G_{13} , ν_{13} , and ν_{12} . [8,13] Due to the aims of this research, work defining material properties as a function of density will be studied. [20] Upon placing portions of femoral shaft in a four-point bending test, Keller et al. found an exponential relationship between Young's modulus and apparent density. However, the value of the exponent varies with the anatomical location of the specimen. Also, at a future time, some smaller portions of the bones may be modeled to include some of the microstructural information which is becoming better understood. [34]

Loading

Forces will be applied to the bones at the locations of muscle attachment. The directions of the experimentally determined forces will be same as those which are actually applied to the bones.

Boundary Conditions

Other researchers have modeled experiments of bones of the lower extremities, and their boundary conditions have matched the boundaries of their experimental apparatus. In these models of the lower extremity bones, points away from the loads will be constrained in all degrees of freedom. Results will be examined in light of fictitious reactions around these constrained points. The models may be reanalyzed with different boundary conditions to eliminate these fictitious reactions from the results.

CONCLUSIONS AND RECOMMENDATIONS

A bicycle ergometer system has been developed to determine forces acting in specific muscles and muscle groups for both cycling and isometric exercise. Data has been collected for static loading and will be collected for cycling in both an earth-based laboratory and on the KC-135. Once the data is analyzed, the forces will be entered into finite element models of bones of the lower extremities.

A finite element model of the tibia-fibula has been generated from the experimental subject's MRI data. Models will be generated for the calcaneus and the femur. Further work needs to be done to automate the process for generating geometry from MRI slices.

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